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Kilometre-scale carbonate mounds in basinal strata: implications for base-metal mineralization in the Mesoproterozoic Arctic Bay and Society Cliffs formations, Borden Basin, Nunavut

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Turner, E.C., 2004: Kilometre-scale carbonate mounds in basinal strata: implications for base-metal mineralization in the Mesoproterozoic Arctic Bay and Society Cliffs formations, Borden Basin, Nunavut; Geological Survey of Canada, Current Research 2004-B4, 12 p.

Abstract: Huge dolostone buildups (>200 m thick, >4 km across) grew in deep water during uppermost Arctic Bay Formation shale deposition in the northwestern Milne Inlet Graben, Borden Basin (Mesoproterozoic). Mounds and coeval shale are temporally equivalent to the lower Society Cliffs Formation in the southeastern part of the graben. Mounds protrude through the Society Cliffs basinal carbonate laminite interval into the lower Victor Bay Formation shale, both of which accumulated around the relict topography of defunct mounds. Absence of stromatolitic fabric and an exclusively basinal location indicate that mounds are not normal Proterozoic photic-zone reefs; scattered distribution, lack of preference for particular substrate types or specific facies tracts, and mound elongation parallel to nearby syndepositional faults suggest that mounds grew around cold seeps. Mounds may serve as landmarks for areas of long-lived permeable faults through which early and late mineralizing fluids migrated. The geometry of buried mounds may also be critical to localizing later Nanisivik-style mineralization.

Résumé : D'immenses monticules de dolomie (d'une épaisseur de plus de 200 m et d'un diamètre de plus de 4 km) se sont formés en eau profonde pendant le dépôt des shales de la partie sommitale de la Formation d'Arctic Bay dans la partie nord-ouest du graben de Milne Inlet dans le bassin de Borden (Mésoprotérozoïque). Des monticules et des shales contemporains sont équivalents du point de vue temporel à la partie inférieure de la Formation de Society Cliffs de la partie sud-est du graben. Les monticules dépassent à travers l'intervalle des laminites carbonatées de bassin de la Formation de Society Cliffs dans le shale de la partie inférieure de la Formation de Victor Bay, les deux s'étant accumulés autour des vestiges topographiques des anciens monticules. La présence des monticules exclusivement dans un bassin et l'absence de structure stromatolitique indiquent que ces monticules ne sont pas des récifs protérozoïques normaux de zone euphotique; l'éparpillement des monticules, le fait qu'ils ne présentent aucune préférence quant au substrat ou au macrofaciès et leur forme allongée parallèlement à des failles synsédimentaires voisines portent à croire qu'ils se sont accumulés près de suintements froids. Ces monticules pourraient servir de repères pour des zones de failles perméables de longue durée par lesquelles auraient migré des fluides minéralisateurs précoces et tardifs. La géométrie des monticules enfouis pourrait également s'avérer critique pour la localisation de minéralisations de style Nanisivik plus tardives.

GEOLOGICAL SETTING

The Milne Inlet Graben, one of three grabens in the aulacogenic Borden Basin (Mesoproterozoic; ca. 1.2 Ga), has a 300 km long northwest-trending wedge-shaped exposure area on northwestern Baffin Island (Fig. 1) and contains strata of the Bylot Supergroup (Fig. 2). It is characterized by syndepositional, repeatedly reactivated, northwest-trending dominant faults and variably oriented subsidiary structures; some of these faults were later injected with gabbro of the ca. 723 Ma Franklin dyke system (Heaman et al., 1992; Pehrsson and Buchan, 1999). The general structure and stratigraphy of the basin have been described by Jackson and Iannelli (1981) and by Iannelli (1992). Large (>200 m thick, >4 km wide), hitherto unrecognized dolostone mounds are present in the middle part of the Bylot Supergroup, within an interval containing the Arctic Bay (predominantly shale; Jackson and Iannelli, 1981; Iannelli, 1992), Society Cliffs (predominantly dolostone; Geldsetzer, 1973; Kah and Knoll, 1996; Kah, 1997; Kah et al., 2001; Turner, 2003a), and Victor Bay (shale overlain by dolostone; Sherman et al., 2000, 2001) formations.

This work arises from a study focused on the structural, stratigraphic, and sedimentological controls on the distribution, nature, and origin of the numerous Pb/Zn (± Cu, F, Ag) showings known from the Milne Inlet Graben (Jackson and Sangster, 1987; Sangster, 1998). The most important of these mineral deposits is the Nanisivik Zn-Pb-Ag orebody (mined 1976–2002), located in an area shown here to have complex mound-intermound geometric and sedimentological relations. Known mineralization throughout the Milne Inlet Graben is constrained to distinct lithofacies and/or stratigraphic levels of the Society Cliffs Formation (e.g. Turner, 2003b), a complex unit whose sedimentology and stratigraphy in the western two-thirds of the basin are here shown to have been locally very strongly affected by development of the unusual dolostone mounds.

MOUND GEOMETRY AND LATERAL FACIES RELATIONS

Hitherto unrecognized mounds have been identified in five areas (Fig. 1, 3) — from west to east: (1) St. Georges Society Cliffs, near Arctic Bay (Uluksan mound); (2) Nanisivik, beneath the Nanisivik orebody and in core from the Deb

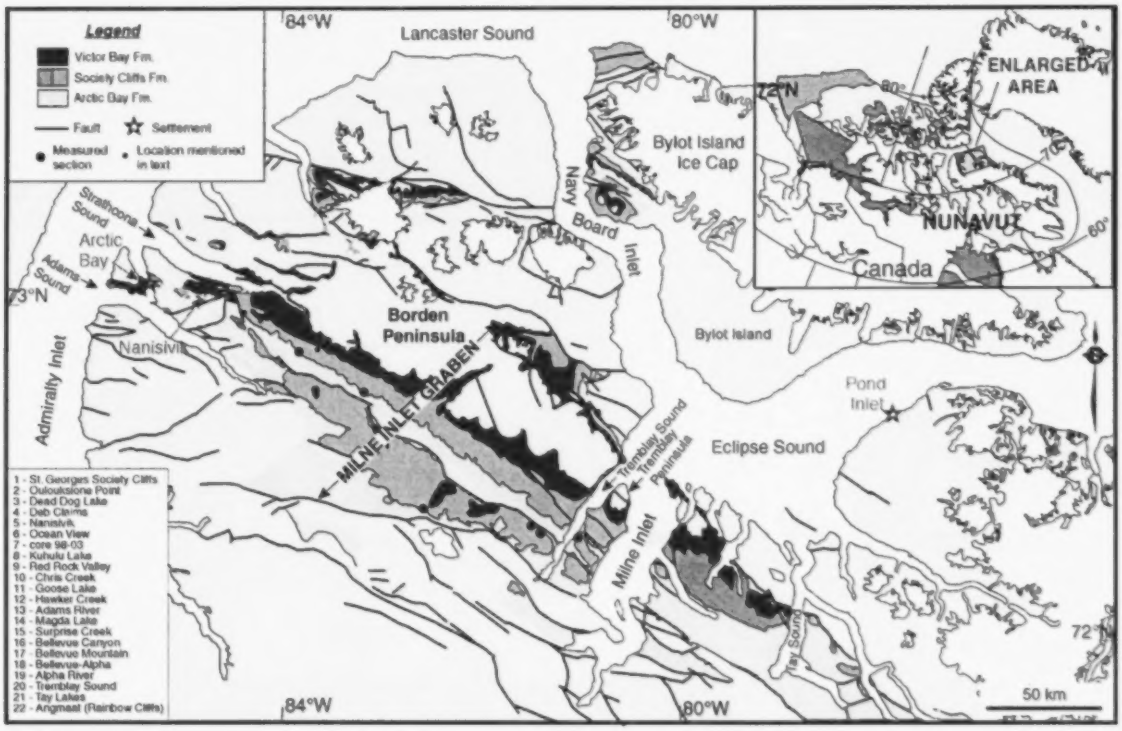


Figure 1. *Map of northernmost Baffin Island showing the distribution of mounds, formations associated with mounds, major environmental divisions within the Society Cliffs Formation, major faults in the Borden Basin, 2002 and 2003 sections, drill cores from the Nanisivik Mine area, and other locations mentioned in text.*

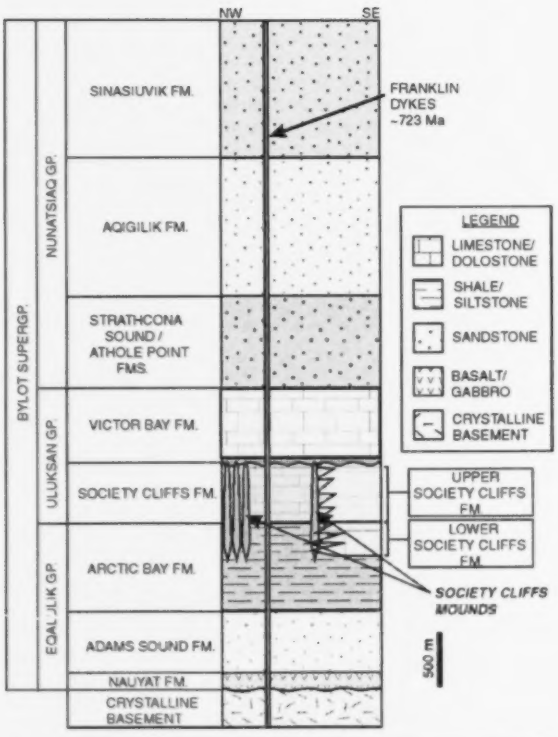


Figure 2.

Schematic stratigraphy of the Bylot Supergroup, northern Baffin Island. Lateral thickness variation and relative thickness of subunits in the Society Cliffs Formation cannot be depicted accurately.

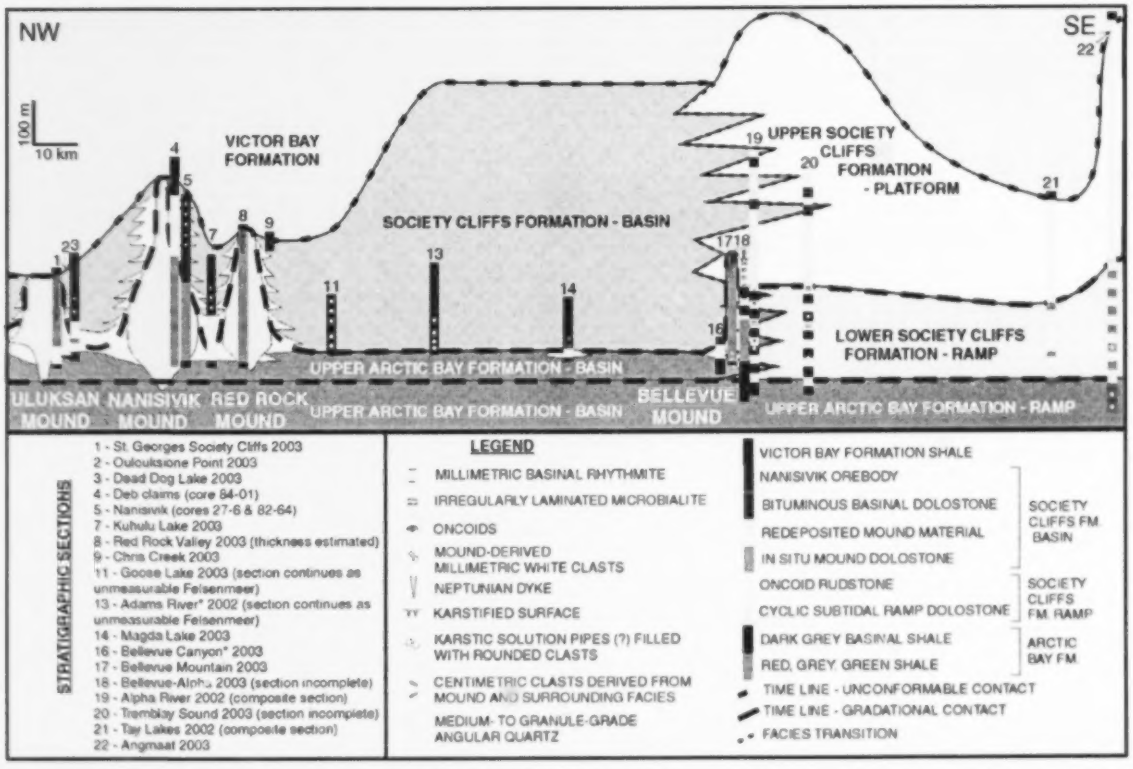
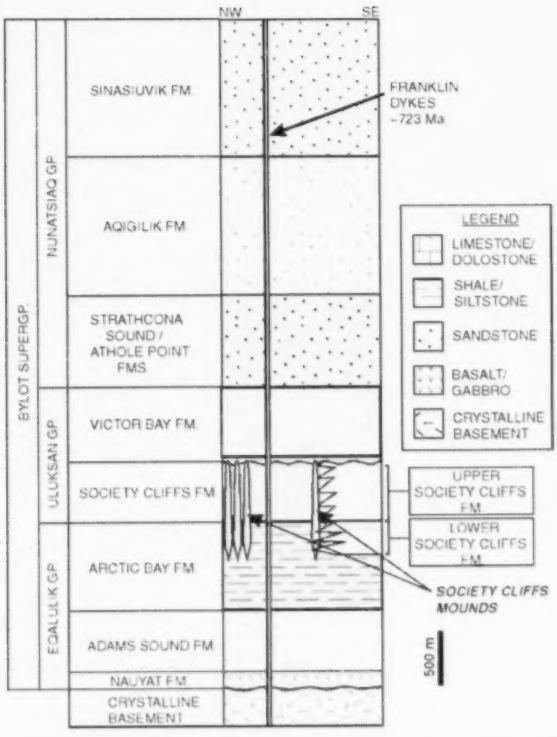

NW
SE
100 m
10 km
VICTOR BAY FORMATION
SOCIETY CLIFFS FORMATION - BASIN
UPPER SOCIETY CLIFFS FORMATION - PLATFORM
LOWER SOCIETY CLIFFS FORMATION - RAMP
UPPER ARCTIC BAY FORMATION - BASIN
UPPER ARCTIC BAY FORMATION - RAMP
ULUKSAN MOUND
NANISIVIK MOUND
RED ROCK MOUND
BELLEVUE MOUND
STRATIGRAPHIC SECTIONS
1 - St. Georges Society Cliffs 2003
2 - Oulouksione Point 2003
3 - Dead Dog Lake 2003
4 - Deb claims (core 84-01)
5 - Nanisivik (cores 27-6 & 82-64)
7 - Kuhulu Lake 2003
8 - Red Rock Valley 2003 (thickness estimated)
9 - Chris Creek 2003
11 - Goose Lake 2003 (section continues as unmeasurable Felsenmeer)
13 - Adams River* 2002 (section continues as unmeasurable Felsenmeer)
14 - Magda Lake 2003
16 - Bellevue Canyon* 2003
17 - Bellevue Mountain 2003
18 - Bellevue-Alpha 2003 (section incomplete)
19 - Alpha River 2002 (composite section)
20 - Tremblay Sound 2003 (section incomplete)
21 - Tay Lakes 2002 (composite section)
22 - Angmaat 2003
LEGEND
MILLIMETRIC BASINAL RHYTHMITE
IRREGULARLY LAMINATED MICROBIALITE
ONCOIDS
MOUND-DERIVED MILLIMETRIC WHITE CLASTS
NEPTUNIAN DYKE
KARSTIFIED SURFACE
KARSTIC SOLUTION PIPES (?) FILLED WITH ROUNDED CLASTS
CENTIMETRIC CLASTS DERIVED FROM MOUND AND SURROUNDING FACIES
MEDIUM- TO GRANULE-GRADE ANGULAR QUARTZ
VICTOR BAY FORMATION SHALE
NANISIVIK OREBODY
BITUMINOUS BASINAL DOLOSTONE
REDEPOSITED MOUND MATERIAL
IN SITU MOUND DOLOSTONE
SOCIETY CLIFFS FM. BASIN
ONCOID RUDSTONE
CYCLIC SUBTIDAL RAMP DOLOSTONE
SOCIETY CLIFFS FM. RAMP
DARK GREY BASINAL SHALE
RED, GREY, GREEN SHALE
ARCTIC BAY FM.
TIME LINE - UNCONFORMABLE CONTACT
TIME LINE - GRADATIONAL CONTACT
FACIES TRANSITION

Figure 3. *Simplified stratigraphic sections from the Milne Inlet Graben, showing mound locations and correlations between shallow-ramp and basinal lithofacies of the Arctic Bay and Society Cliffs formations. Asterisks indicate that complete section thicknesses were taken from Iannelli (1992) for sections only partially measured in the present study.*



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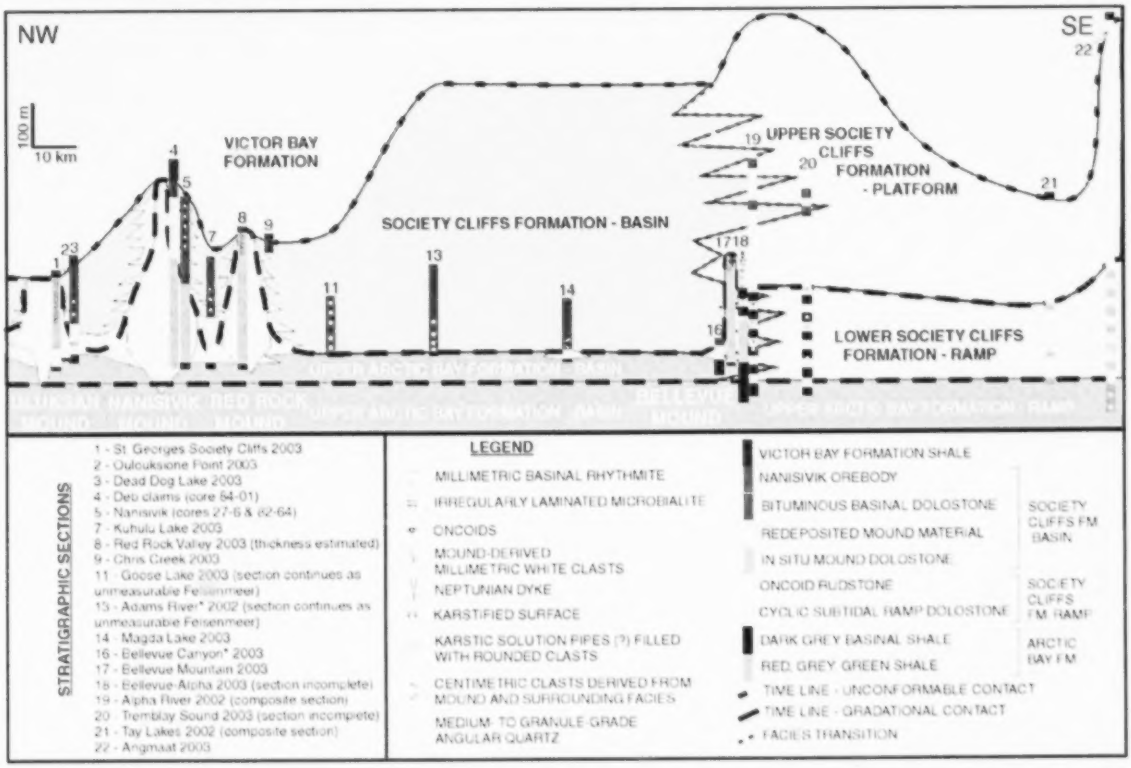

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claims (Nanisivik mound); (3) Red Rock valley (Red Rock mound); (4) Magda Lake (Magda mound); and (5) Bellevue Mountain (Bellevue mound). At three of these locations (Uluksan, Red Rock, and Bellevue mounds), mound core facies are exposed as dramatic cliffs. At Magda Lake, only peripheral facies are exposed, and at Nanisivik, mound facies are recognized in outcrop on the hill above the mine portal, and core facies in subsurface from drill core.

Uluksan mound

The St. Georges Society Cliffs loom over Adams Sound for approximately 10 km along the south coast of the Uluksan Peninsula; faint, laterally discontinuous, decametre-scale colour banding dips very slightly northward, and there is no evidence of folding. Cliffs 250 m high in the middle of the outcrop length rise directly from sea level (Fig. 4A, 5A); in this area, depth soundings reportedly place the top of the cliff-base talus slope at >60 m below sea level. East and west of the central area, cliff bases pass into talus slopes above sea level, reflecting the underlying locally exposed dark grey shale. The contact between shale and massive dolostone rises to 100 m above sea level at the eastern end of the sea cliffs, where the lowermost 10 m consist of unlayered, chaotic intraclast floatstone (Fig. 5B). Surfaces sparsely littered with slumped and folded shale and carbonate clasts downlap subtly onto the underlying shale.

Although colour banding is present, the sea-cliff dolostone contains no structure at outcrop or hand-sample scale. A 200 m section measured where the cliff base is close to sea level (St. Georges Society Cliffs; Fig. 1, 3, 4A, 5A) shows that the uppermost part of the dolostone cliffs contains irregular conglomeratic pipes and lenses, with red-stained dolomitic cement between subrounded dolostone clasts (Fig. 5C). Near the top of the sea cliffs is a planar, inaccessible upper surface to this dolostone (Fig. 5D); a thin succession (~30 m) of laminated dolostone overlain by imbricated and rosetted tabular intraclast rudstone passes northward (stratigraphically upward) into lower Victor Bay Formation shale approximately 300 m north of the cliff top.

A section measured north of the sea cliffs (Dead Dog Lake; Fig. 1, 3, 4A) passes upward and northward from homogeneous dolostone and rubbly, dolomite-cemented conglomerate into matrix-supported, chaotic laminite-intraclast rudstone overlain by laminated basinal rocks with intercalated centimetric to decimetric massive dolostone layers. Together, these observations depict a lenticular mound on the order of 8 km in length, 250 m thick at its centre, tapering

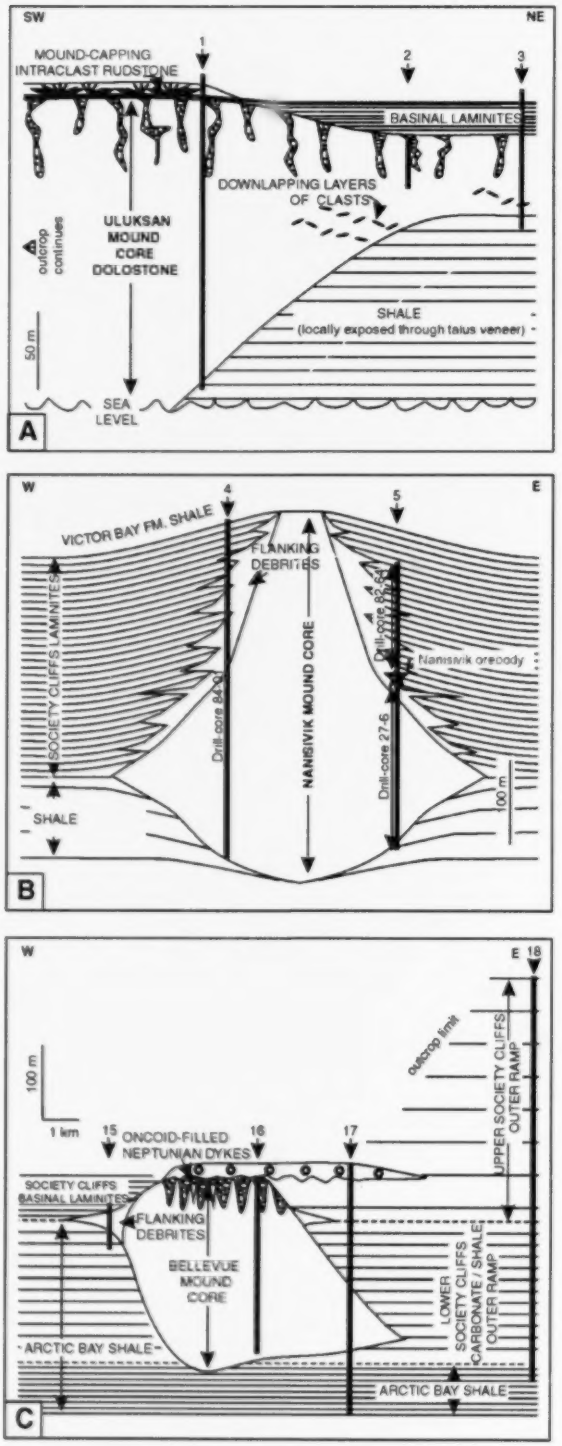


Figure 4. *Schematic diagrams of mounds. **(A)** Uluksan mound, exposed in sea cliff on Adams Sound (only eastern end is shown). **(B)** Nanisivik mound, from drill core. Mound geometry is uncertain; mound core may be west of the Deb claims core. **C)** Bellevue mound, exposed on south wall of Alpha River valley (diagram is mirror-image view of outcrop).*

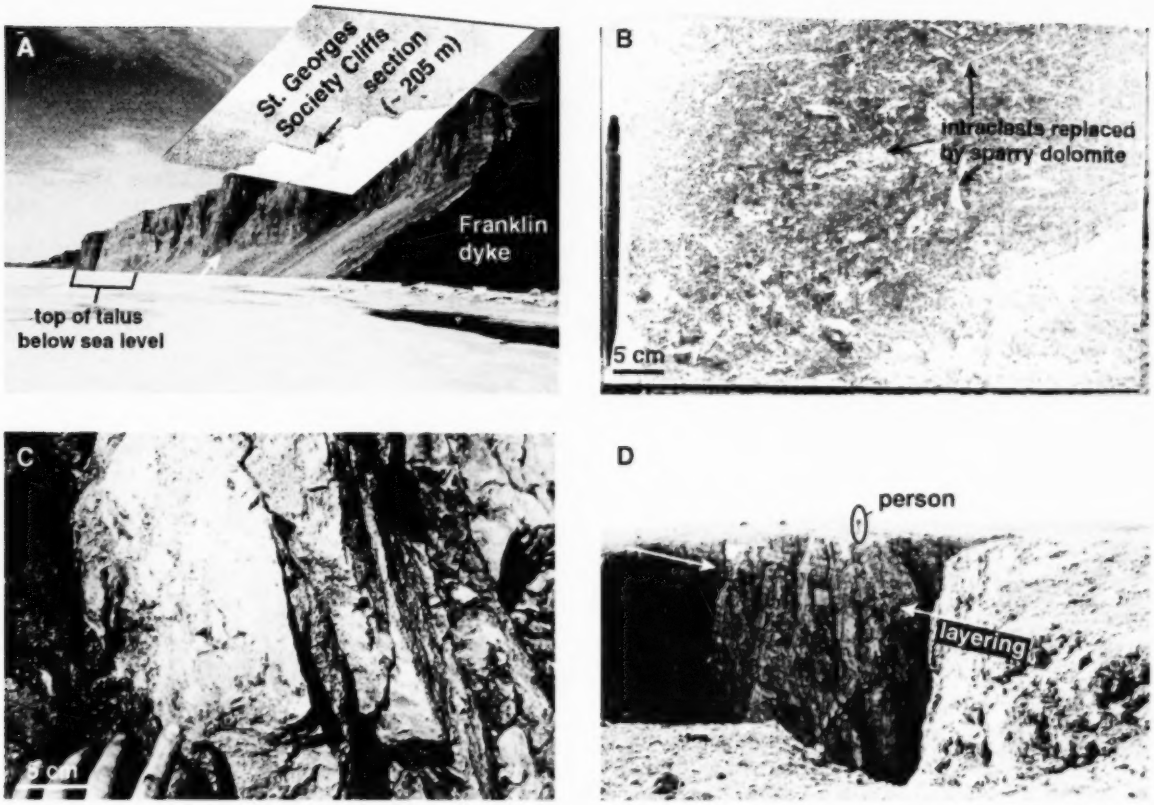


Figure 5. *Uluksan mound. **(A)** Exposure at St. Georges Society Cliffs; view to west-northwest. Central cliffs drop directly to sea ice, whereas shale-dolostone contact (at top of modern talus) rises both westward and eastward. **(B)** Lower intraclastic facies (clasts replaced by coarse dolomite). **(C)** Conglomerate and interstitial coarse red dolomite (Oulouksione point). **(D)** Layered dolostone overlying massive mound rock.*

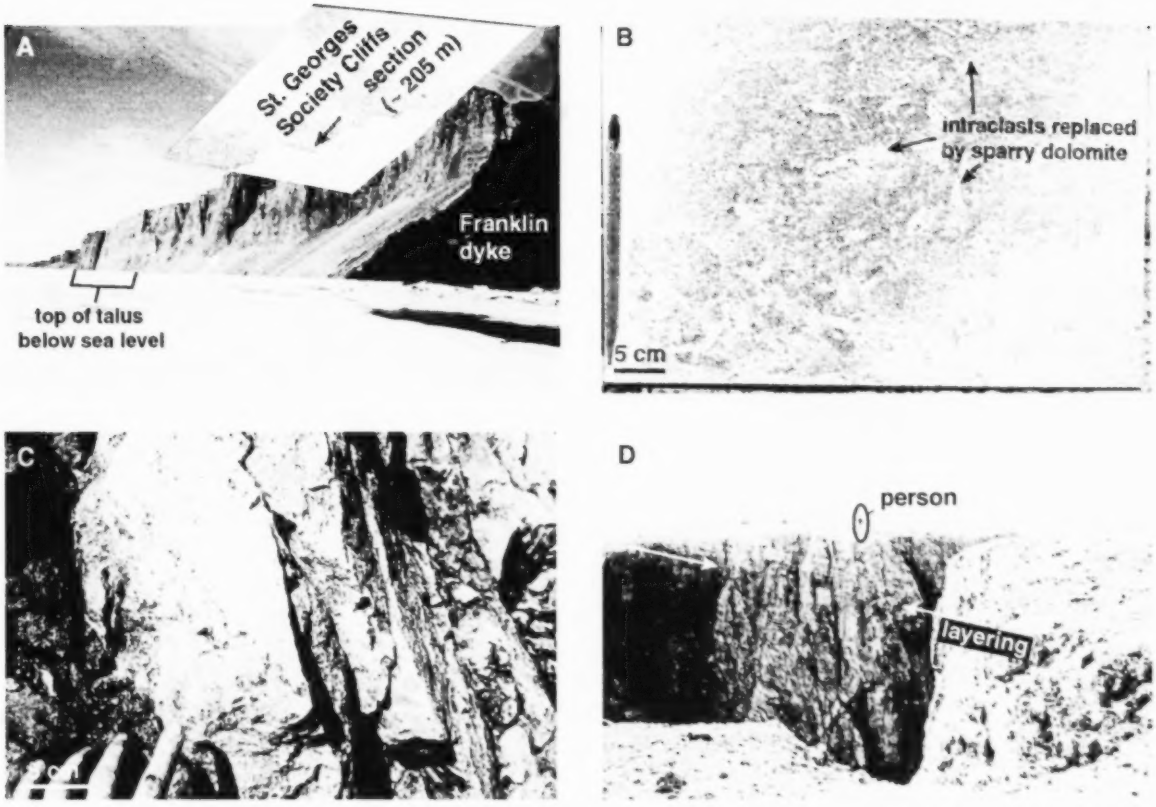
sharply to the north, and tapering gently to the west and east; the mound appears to have a west-east elongation, roughly parallel to the sea cliff.

Nanisivik mound

Core drilled down from the lowest level of the mine (drill core 27-6) reveals 188 m of homogeneous pale mound dolostone below the orebody; the hill overlying the mine's main portal (drill core 82-64 and outcrop) contains mound-flank debrites and a wedge of intact mound dolostone, intercalated with basinal laminite (total thickness 135 m; interfingered mound material in outcrop was erroneously mapped as small anticlines in Patterson et al., 2003). Mound facies underlie the orebody, which is overlain by and laterally equivalent to basinal facies intercalated with mound-clast debrites; this indicates that the orebody is situated over a mound flank. Core from the Deb claims, 3 km west of Nanisivik (core 84-01), contains 250 m of mound facies overlain by 138 m of mound-dolostone debrites and 37 m of basinal laminite, followed by Victor Bay shale. These cores define a mound that is distinct from the Arctic Bay and Red Rock valley buildups, but whose geometry is unclear (Fig. 4B). The featureless mound lithofacies in the Nanisivik area was recognized by Clayton and Thorpe (1982), who noted that "most of the formation" in the Nanisivik area had "undergone recrystallization to…marble".

Red Rock mound

The 12 km long Red Rock valley cuts through a north-northwest-trending mound (at least 20 km x 5 km in areal extent; Fig. 6A). A partly exhumed mound top has pronounced topography, against which compositional layering in the compactionally draped lower Victor Bay shale abuts (Fig. 6B). The northern part of the mound passes westward to a section (Kuhulu Lake) in which the dolostone overlying Arctic Bay Formation shale consists of massive, matrix-supported intraclast wackestone to packstone debrites and turbidites (~160 m of section consisting of angular, equant, millimetric to centimetric homogeneous dolostone clasts floating in pale grey dolomudstone matrix; Fig. 7A, B). This is gradationally overlain by 60 m of basinal laminite, followed by Victor Bay shale. In the area 1 km east of Red Rock



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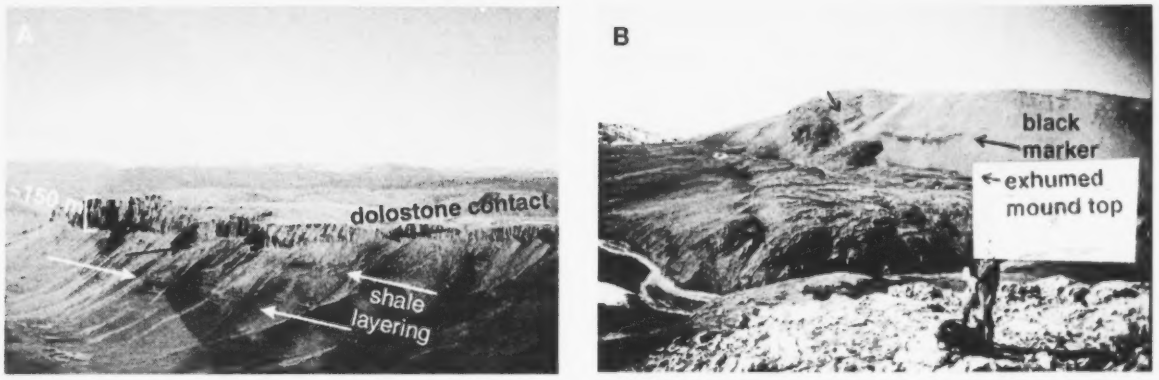


Figure 6. *Red Rock mound. (A) Contact between shale and overlying red-stained, massive mound rock rises to southeast (right). View to the north. (B) Relict mound topography: black layer in Victor Bay shale laps onto mound-top paleotopography, which rises to the north. View to the northwest.*

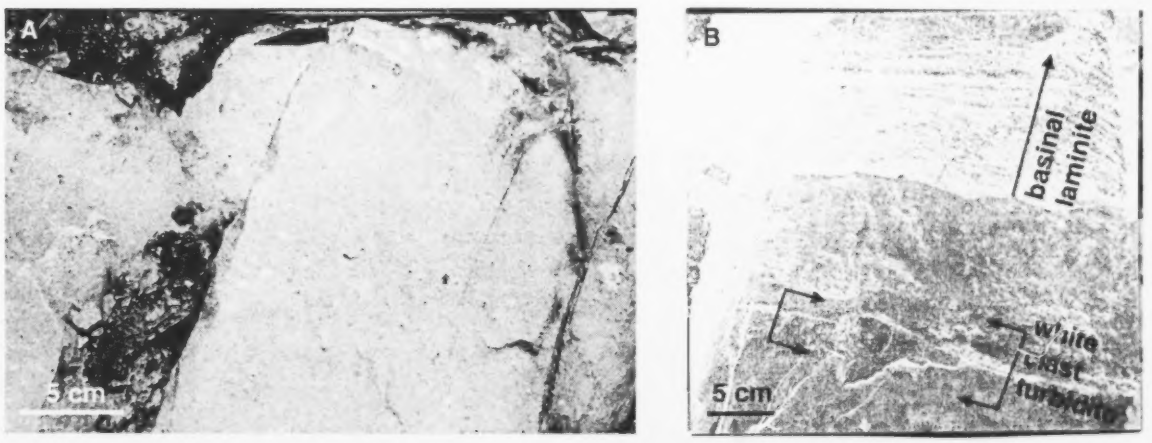


Figure 7. *Kuhulu Lake section. (A) Floatstone debrite of pale mound-derived clasts. (B) Mound-clast turbidite interlayered with basinal laminite lithofacies.*

valley, the mound tapers, and laminite lithofacies abut its upper flank. Five kilometres to the east (Chris Creek section), 30 m of basinal laminite lithofacies and laminite-clast debrites are exposed beneath Victor Bay shale, but the composition of underlying rocks is unknown. The mound appears, therefore, to taper sharply to mound flanks both west and east of the long valley exposure, suggesting a north-northwest-trending elongation, roughly parallel to the valley itself.

Magda mound

In the Magda Lake section, shale is overlain by 17 m of mound-derived olistoliths and debrite-turbidite intervals, and >100 m of basinal laminite lithofacies (Fig. 8A, B). This indicates proximity to a mound that has not been identified in outcrop.

Bellevue mound

The >200 m thick Bellevue mound (Fig. 4C, 9A, B) separates exposures of peritidal ramp facies to the southeast from basinal laminite lithofacies to the northwest; mound facies are also exposed north of the Alpha River, and can be traced on airphotos northward to the contact with the Victor Bay shale. In Landsat 5 images using RGB 741 bands (band 7 highlights iron oxide), mound rock forms a distinct north-trending swath approximately 4 km wide between unreflective ramp dolostone to the east and highly reflective basinal dolostone to the west.

A section measured through the Bellevue mound (Fig. 9B) consists of approximately 50 m of weakly layered, chaotic intraclast debrites, turbidites and clasts of mound material overlain by 190 m of massive, unlayered mound

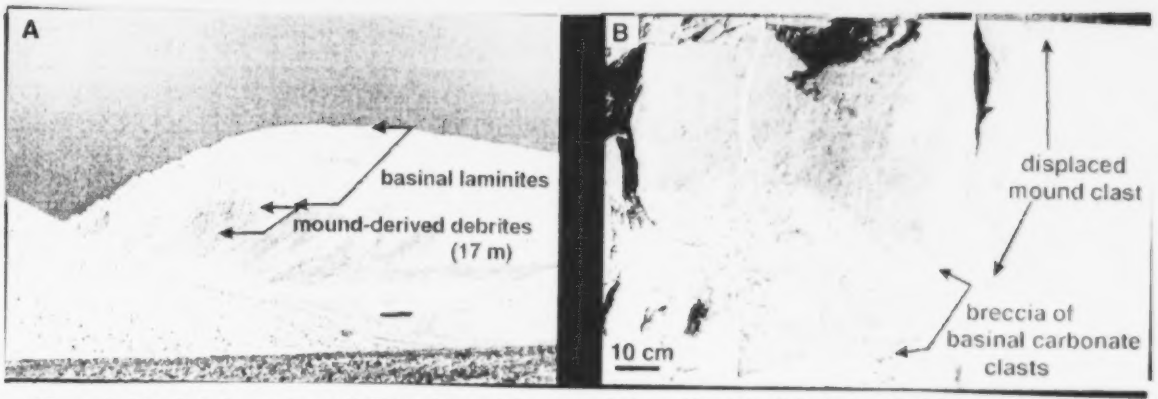


Figure 8. *Magda Lake section. **(A)** Thin white unit between shale and laminite lithofacies (dark brown) is a common manifestation of mound peripheral facies. **(B)** Chaotic debrite/olistolith in basal unit.*

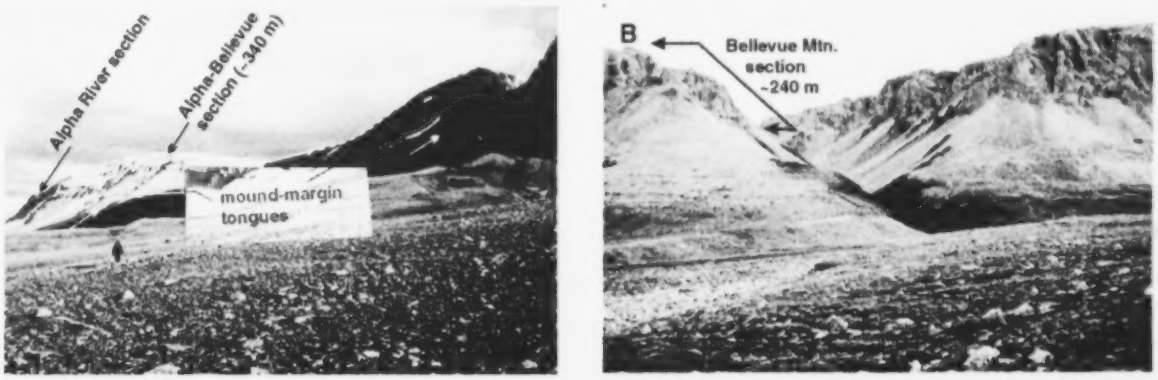
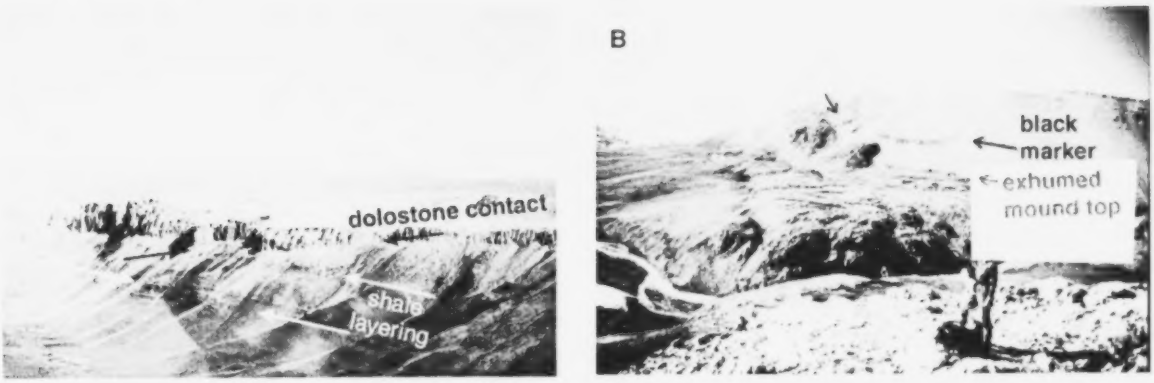


Figure 9. *Bellevue mound. **(A)** Layered rocks in distance are lower Society Cliffs shale/carbonate and upper Society Cliffs outer ramp; eastern end of photo is mound core (in shadow). **(B)** Basinal shale (black, recessively weathering and talus-covered) overlain by mound (pale, resistantly weathering cliffs).*

dolostone, with dolomite-cemented conglomeratic pipes and lenses near the top. Oncoid floatstone-rudstone present in talus and in neptunian dykes close to the top of the exposure represents a mound-capping facies. The massive mound-core facies passes basinward (in the Bellevue Canyon section) into intraclast debrites, turbidites, and creep-folded carbonate mudstone layers (total ~53 m) underlain by shale and overlain by basinal laminite lithofacies. Rampward, however (Bellevue-Alpha section), the mound pinches out as two wedges: one corresponds to a shale-dominated interval in the lower Society Cliffs Formation, and the other, equivalent to the mound top, corresponds to the lower–upper Society Cliffs transition. Oncolitic dolostone units in strata immediately east of the mound top (Bellevue-Alpha section) indicate that topographic relief at the eastern margin of the mound was almost completely erased by the lower to upper Society Cliffs transition. At the Alpha River section, 4 km east of the mound flank, an east-deepening paleoslope is indicated by imbricated ribbon carbonate clasts in the outer part of the lower Society Cliffs ramp (Turner, 2003a), which contradicts the general westward deepening of the ramp, and suggests that mound topography influenced local sedimentation during mound growth.

MOUND INTERNAL COMPOSITION

Medium-crystalline dolostone of mound cores weathers pale brown to white, and is commonly red-stained owing to the weathering of scattered specular hematite pods. In spite of local colour banding (Fig. 5A, 10A), outcrop is generally devoid of compositional or textural layering, and commonly lacks hand-sample-scale internal structure. Mound rocks lack the bituminous odour characteristic of enclosing carbonate laminite lithofacies. In the Arctic Bay area and in most of the 84-01 drillcore (Deb claims section), the mound succession consists of featureless, whitish, locally mottled dolostone. In the Red Rock and Bellevue mounds, faintly clotted microbial textures are present (Fig. 10B), defined by millimetric dolomudstone masses separated by millimetric areas of



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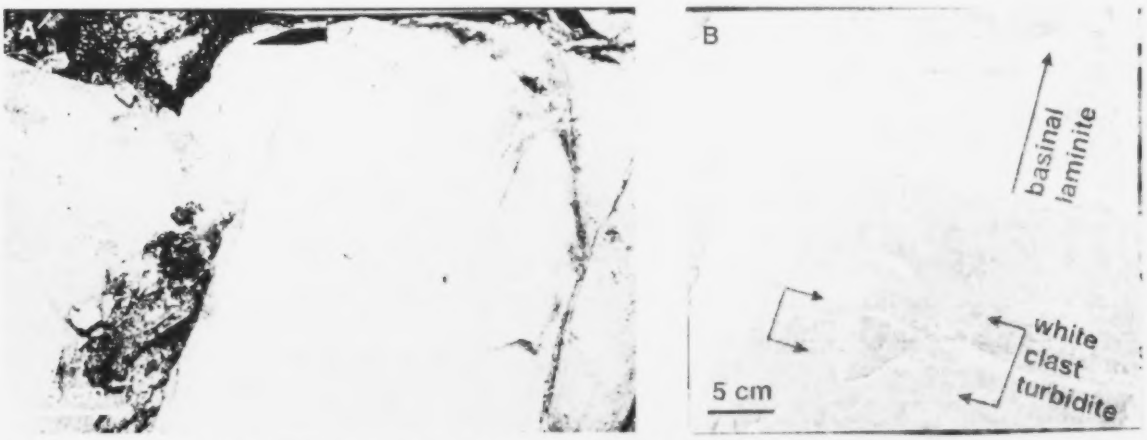

Figure 7. *Kuhulu Lake section. (**A**) Floatstone debrite of pale mound-derived clasts. (**B**) Mound-clast turbidite interlayered with basinal laminite lithofacies.*

valley, the mound tapers, and laminite lithofacies abut its upper flank. Five kilometres to the east (Chris Creek section), 30 m of basinal laminite lithofacies and laminite-clast debrites are exposed beneath Victor Bay shale, but the composition of underlying rocks is unknown. The mound appears, therefore, to taper sharply to mound flanks both west and east of the long valley exposure, suggesting a north-northwest-trending elongation, roughly parallel to the valley itself.

Magda mound

In the Magda Lake section, shale is overlain by 17 m of mound-derived olistoliths and debrite-turbidite intervals, and >100 m of basinal laminite lithofacies (Fig. 8A, B). This indicates proximity to a mound that has not been identified in outcrop.

Bellevue mound

The >200 m thick Bellevue mound (Fig. 4C, 9A, B) separates exposures of peritidal ramp facies to the southeast from basinal laminite lithofacies to the northwest; mound facies are also exposed north of the Alpha River, and can be traced on airphotos northward to the contact with the Victor Bay shale. In Landsat 5 images using RGB 741 bands (band 7 highlights iron oxide), mound rock forms a distinct north-trending swath approximately 4 km wide between unreflective ramp dolostone to the east and highly reflective basinal dolostone to the west.

A section measured through the Bellevue mound (Fig. 9B) consists of approximately 50 m of weakly layered, chaotic intraclast debrites, turbidites and clasts of mound material overlain by 190 m of massive, unlayered mound

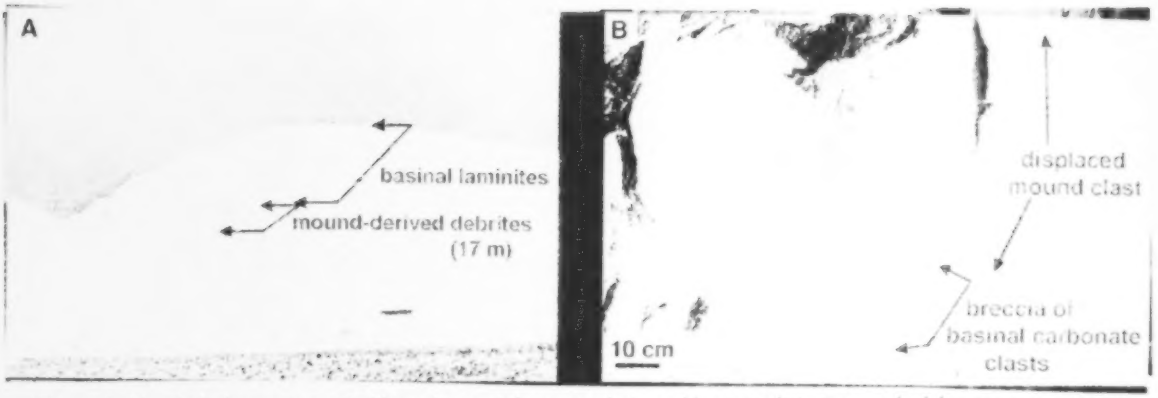

Figure 8. *Magda Lake section. (**A**) Thin white unit between shale and laminite lithofacies (dark brown) is a common manifestation of mound peripheral facies. (**B**) Chaotic debrite olistolith in basal unit.*

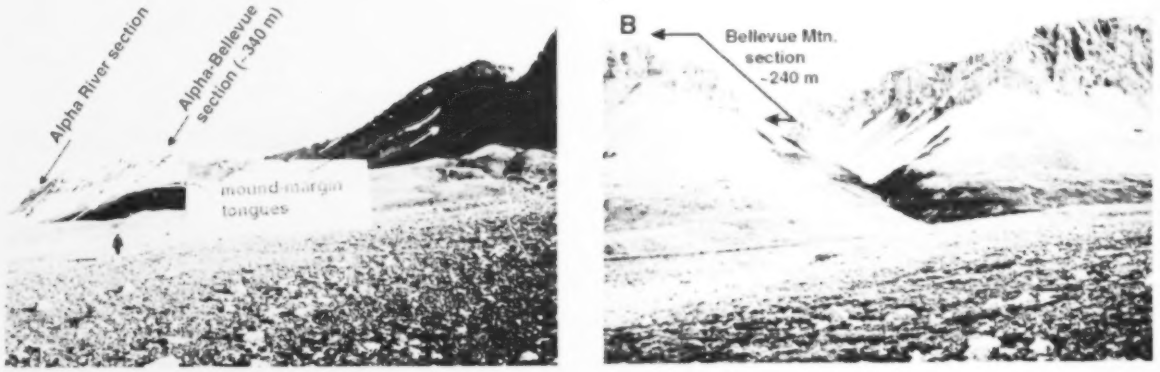

Figure 9. *Bellevue mound. (**A**) Layered rocks in distance are lower Society Cliffs shale carbonate and upper Society Cliffs outer ramp; eastern end of photo is mound core (in shadow). (**B**) Basinal shale (black, recessively weathering and talus-covered) overlain by mound (pale, resistantly weathering cliffs).*

dolostone, with dolomite-cemented conglomeratic pipes and lenses near the top. Oncoid floatstone-rudstone present in talus and in neptunian dykes close to the top of the exposure represents a mound-capping facies. The massive mound-core facies passes basinward (in the Bellevue Canyon section) into intraclast debrites, turbidites, and creep-folded carbonate mudstone layers (total ~53 m) underlain by shale and overlain by basinal laminite lithofacies. Rampward, however (Bellevue-Alpha section), the mound pinches out as two wedges: one corresponds to a shale-dominated interval in the lower Society Cliffs Formation, and the other, equivalent to the mound top, corresponds to the lower–upper Society Cliffs transition. Oncolitic dolostone units in strata immediately east of the mound top (Bellevue-Alpha section) indicate that topographic relief at the eastern margin of the mound was almost completely erased by the lower to upper Society Cliffs transition. At the Alpha River section, 4 km east of the mound flank, an east-deepening paleoslope is indicated by imbricated ribbon carbonate clasts in the outer part of the lower Society Cliffs ramp (Turner, 2003a), which contradicts the general westward deepening of the ramp, and suggests that mound topography influenced local sedimentation during mound growth.

MOUND INTERNAL COMPOSITION

Medium-crystalline dolostone of mound cores weathers pale brown to white, and is commonly red-stained owing to the weathering of scattered specular hematite pods. In spite of local colour banding (Fig. 5A, 10A), outcrop is generally devoid of compositional or textural layering, and commonly lacks hand-sample-scale internal structure. Mound rocks lack the bituminous odour characteristic of enclosing carbonate laminite lithofacies. In the Arctic Bay area and in most of the 84-01 drillcore (Deb claims section), the mound succession consists of featureless, whitish, locally mottled dolostone. In the Red Rock and Bellevue mounds, faintly clotted microbial textures are present (Fig. 10B), defined by millimetric dolomudstone masses separated by millimetric areas of

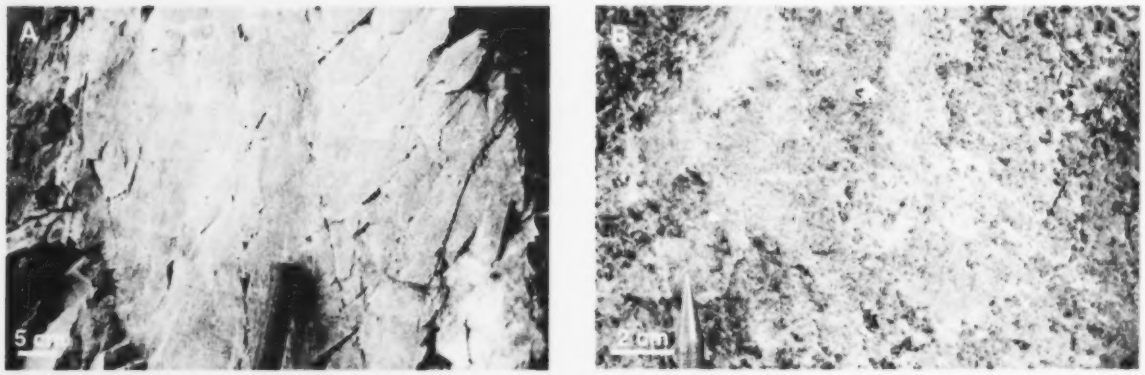

Figure 10. *Mound internal textures. (A) Featureless mound dolostone with discontinuous colour bands (Uluksan mound). (B) Weakly clotted mound dolostone (Bellevue mound).*

somewhat coarser, isopachous, medium-crystalline dolomite crystals; there is no vertical variation in this facies. Millimetric to centimetric thromboids and intervening multilayer isopachous cements are present in the lowest 64 m of core 84-01 (Deb claims).

The uppermost parts of most mound exposures (~35 m in Bellevue mound, 50 m in Uluksan and Red Rock mounds) are characterized by irregular masses of rounded clasts (Fig. 5C) and cement-filled veinlets, separating areas of unaltered mound lithofacies. Veinlets and interstices between the clasts are lined with isopachous, medium-crystalline, commonly red-stained dolomite.

INTERPRETATION

Mound growth

Although growth of all known mounds (Fig. 1, 11) appears to have begun during deposition of upper Arctic Bay shale in the west and lower Society Cliffs strata in the east (*see* Turner, 2004b), it is impossible to assess the contemporaneity of mound nucleation, because the stratigraphically lowest mound dolostone is always underlain by shale lacking regionally traceable units. No particular substrate type appears to have been necessary for mound nucleation. Mound location (Fig. 1, 3) bears no relation to facies tracts in the upper Arctic Bay Formation, which Jackson and Iannelli (1981) showed to have a significant lateral facies change in the Milne Inlet area, 30 km east of the easternmost known mound, or in the Society Cliffs Formation ramp, with an inflection point in the Milne Inlet area (Jackson and Iannelli, 1981; Kah, 1997). In the westernmost part of the basin (region west of Red Rock valley), mounds seem to have coalesced to cover most or all of the basin floor.

Mound-growth termination coincided temporally with the change from shale to carbonate laminite lithofacies in the western, basinal area, and with the lower-ramp to upper-platform transition in the eastern area. The enigmatic conglomeratic masses on all mound tops may record shallowing and karstification. Basinal carbonate laminite then accumulated around the relict topography of the mounds. Locally, layering might have had the same angle as underlying mound slopes, leading to gravitational failure and deposition of laminite-clast debrites (as in Dead Dog Lake and Chris Creek sections). The extinct mounds continued to be impressive topographic features throughout the remainder of Society Cliffs Formation time and even, as in the Red Rock valley area, into Victor Bay Formation time.

Stratigraphic positions of mound tops and sedimentological development of mound-capping facies are variable. In the southeast, significant mound-derived debris appears to have been shed mainly during the transition from basinal shale to basinal carbonate laminite deposition, at the end of mound growth. The Bellevue mound underwent subaerial erosion and karstification during this transition, followed by re-immersion, development of oncoid shoals over the mound top, and concomitant formation of oncoid-filled neptunian dykes that crosscut karstic features. The Nanisivik and Red Rock mounds are associated with thick, unbedded accumulations of millimetric mound-derived clasts, commonly intercalated with basinal laminite, suggesting that they might have stood higher and undergone extensive erosion after growth. After exposure and karstification of its upper surface, the Uluksan mound was submerged and briefly became the locus of deposition of laminite, followed by storm-influenced shallow-marine intraclast rudstone, and then Victor Bay shale; its topographic relief was eliminated by the end of Society Cliffs Formation time. The Red Rock mound, however, appears to have stood high well into Victor Bay Formation time. Protracted exposure and the succession of bathymetric changes in western mounds indicate a less rapid, but locally complex and erratic, subsidence history for the Society Cliffs Formation in this westernmost part of the graben.

The northeast-trending, elongate Bellevue mound formed during deposition of the lower Society Cliffs Formation in the southeast and upper Arctic Bay shale in the northwest, approximately where benthic carbonate contribution to the outer ramp/slope became negligible and shale-dominated,

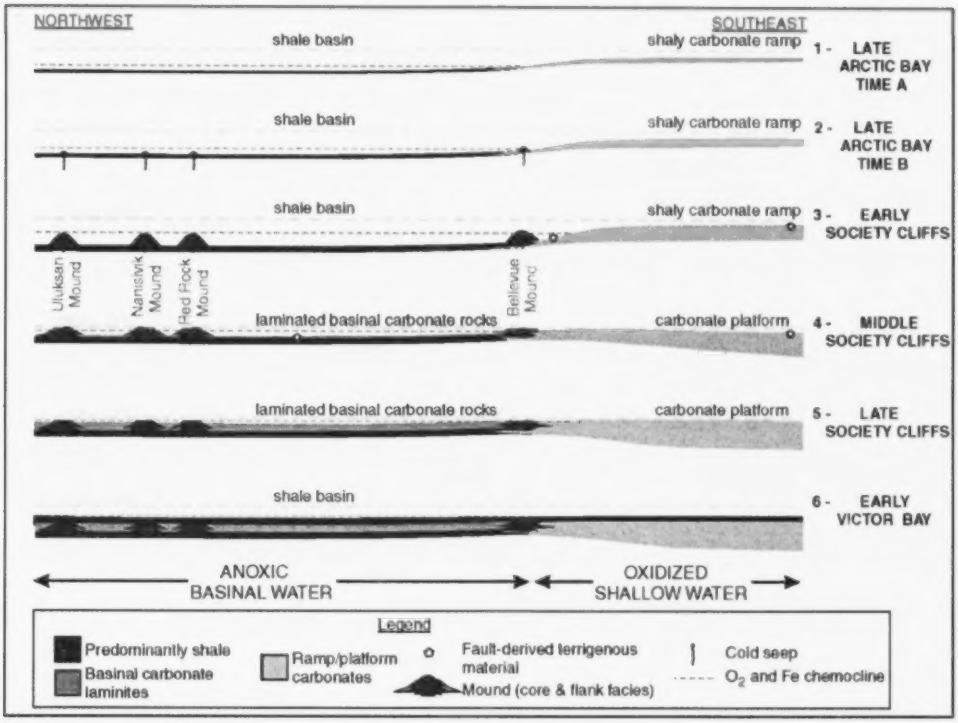

Figure 11. *Proposed history of Arctic Bay–Society Cliffs depositional system.*

and where the later division between peritidal ramp and basinal laminite developed. In its later growth, the mound influenced sedimentation as far as 5 km eastward (near the mouth of the Alpha River), where lower Society Cliffs intraclastic slope deposits contain structures recording an eastward-deepening slope — presumably the slope of the mound, rather than the regionally west-deepening outer ramp/slope. Although the mound's location exaggerates the contrast between western and eastern graben compartments, the outer upper Society Cliffs ramp in the Tremblay Sound area contains intervals of basinal carbonate laminite identical to those in the northwestern basin compartment, indicating that the Bellevue mound did not completely isolate southeastern and northwestern graben compartments from one another. It is interesting that the Bellevue mound trend also separates an eastern area of thick Society Cliffs Formation (typically >600 m) from a western area with variable, but considerably thinner, coeval successions (perhaps as thick as 350 m at St. Georges Society Cliffs, including both equivalent shale and dolostone). This may lend further support to the idea of an important adjustment fault, transverse to basin-controlling normal rift faults, which underlies the Bellevue mound trend and separates shallow- and deep-water domains.

DISCUSSION

Mound origin

A variety of stromatolitic bioherms have been described from the Arctic Bay, Society Cliffs, and Victor Bay formations (Jackson and Iannelli, 1989; Narbonne and James, 1996; Sherman et al., 2000, 2002), but the structures described herein do not compositionally or contextually resemble any of them. Their lack of the stromatolitic framework that is ubiquitous in Proterozoic bioherms, their generally structureless nature, and their deep-water setting indicate that these mounds are not normal photic-zone Proterozoic reefs.

These characteristics, together with the irregular distribution of mounds, the lack of paleogeographic, bathymetric, or substrate controls, the elongate plan shape of some mounds, and the clustering of mounds in an area that existing maps show to have a higher concentration of faults than the average for the basin, suggest that the mounds are likely fossil cold seep deposits. Fluid and/or gas would have entered the deep basin through fissures developed along basin-controlling normal faults, or subtle cross faults (release faults) that moderated extensional displacement on segments of the major, northwest-trending, graben-controlling normal faults. Subtle

faults at high angles to the main normal faults are common in the Milne Inlet Graben, although they do not necessarily figure on regional-scale published maps. Tectonic activity in the graben during mound growth is demonstrated by the presence of coarse-grained, immature, angular terrigenous material, found near basin-controlling faults in the Arctic Bay–Society Cliffs interval at a variety of locations throughout the Milne Inlet Graben (e.g. Angmaat, Adams River, and Goose Lake areas; Fig. 11; Turner, 2003b). Although no north-trending structure is shown on published maps in the Bellevue mound area, the northwest-trending Red Rock mound is near major northwest-trending gabbro-filled faults, and its trend is collinear with the projected trend of the Tikerakdjuak Fault zone (Iannelli, 1992; Scott and de Kemp, 1998) to the southeast (the fault responsible for terrigenous debrites in lower Society Cliffs strata in the Adams River and Goose Lake sections; Turner, 2003b). The west-trending Uluksan mound is in the vicinity of important west-trending faults (*see* Scott and de Kemp, 1998).

Vaguely clotted mound textures suggest that carbonate precipitation was in some way mediated by organisms. Although various fluid compositions are possible, seeps emerging from conduits through organic-rich Arctic Bay and lower Society Cliffs shale might have contained methane. Methane emerging into anoxic seawater can become oxidized by methanotrophs, resulting in local precipitation of carbonate minerals. Evidence for sulphate-reducing (pyrite-producing) bacteria in mounds is not strong, and sulphur-oxidizing bacteria would have required oxygenated conditions that do not agree with the redox conditions tentatively proposed for this basinal setting (*see* Turner, 2004a). Petrographic and geochemical analysis of mound rocks (to follow) will further define the factors involved in mound formation.

Fluid flow and base-metal prospectivity

Certain aspects of mound growth and distribution have implications for base-metal prospectivity of the Arctic Bay through Victor Bay formations in the Milne Inlet Graben.

First, the inferred syndepositional activity of voluminous fluid/gas systems circulating through dilated faults supports the possible activity of mineralizing fluids early in the Milne Inlet Graben's history. The basin clearly was tectonically active through much of its history, with both extensional and compressional (e.g. Sherman et al., 2002) episodes providing ongoing opportunities for thermally or topographically driven fluid flow. In theory, early (sedex) mineralization could have affected basinal shale of the Arctic Bay or Victor Bay formations, or basinal carbonate rocks of the Society Cliffs Formation. Although the exhalation of fluids inferred to have occurred during lower Society Cliffs time resulted in the precipitation of carbonates rather than base-metal sulphides, fluids vented at other times might have had metalliferous compositions.

Second, the clustering of fault-related mound growth in the western part of the graben corresponds to an area in which sulphide showings are best developed (between the Hawker Creek and Arctic Bay areas), most zinc-rich, and commonly associated with significant or subtle faults, many filled with Franklin gabbro. Showings throughout the Milne Inlet Graben are generally characterized by proximity to a major normal fault with significant displacement, or to a lesser adjustment fault with minor displacement, although the faults may not themselves be significantly mineralized. Because basinal mounds seem to have been controlled by the same set of structural features, they may be a marker for areas of long-lived permeable fault networks that were susceptible to flow of a variety of early and later fluids.

Third, the most impressive mineralization in the graben, the Nanisivik orebody, is geometrically intimately involved with a mound and its flanking sediment (Fig. 12); previous work in the area indicates that the mineralization is localized in a subtle domal structure (Clayton and Thorpe, 1982; Patterson and Powis, 2002; Patterson et al., 2003), and that a gas cap trapped in this dome constrained the horizontal upper surface of the orebody (Arne et al., 1991). Although local folds are shown on existing maps (Scott and de Kemp, 1998; Patterson et al., 2003), there is no regional pattern to their distribution. The area has not experienced significant deformation since the Mesoproterozoic, and so the only possible causes for folding at a scale smaller than the gentle synformal sag occupying the Milne Inlet Graben are (1) local warping of strata during reactivation of underlying rift structures; (2) weak compressional deformation caused by distant orogenesis after deposition of the Victor Bay Formation (Sherman et al., 2002); or (3) local compactional draping of Society Cliffs basinal laminite strata (slightly compactable) and overlying Victor Bay shale (aquiclude) around incompressible, homogeneous mounds. If the latter is the case, then mounds and their associated facies and structures (listed below) are necessary criteria for later Nanisivik-style mineralization in the western Milne Inlet Graben:

1. a slightly dilated fault capable of acting as an aquifer, through which fluid could migrate vertically or laterally;

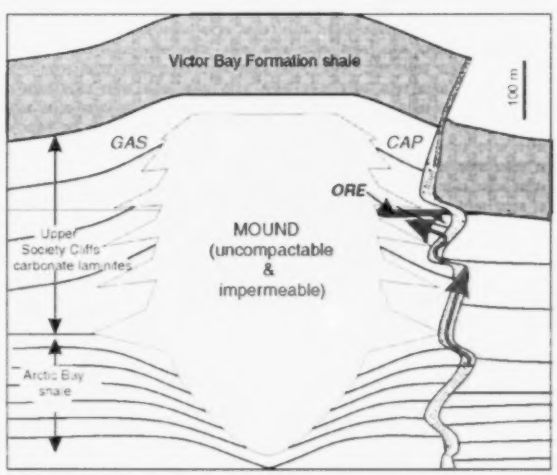

Figure 12. *Proposed facies distributions and structural geometry required for Nanisivik-type orebody.*

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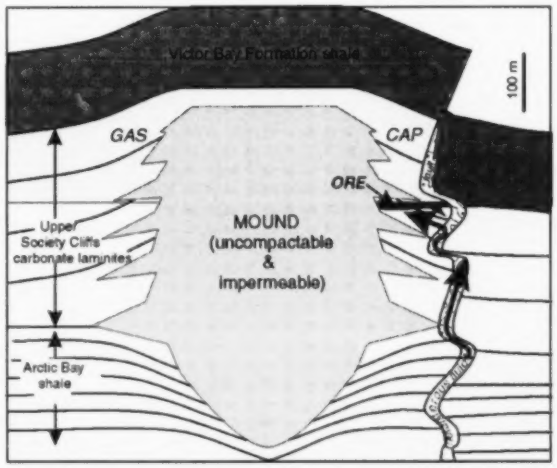

Figure 12. *Proposed facies distributions and structural geometry required for Nanisivik-type orebody.*

2. permeable host dolostone of the upper Society Cliffs laminated facies, through which metalliferous fluid could migrate updip after bleeding from the fault;

3. a subtle domal trap, likely caused by minor compactional doming of basinal laminite lithofacies and/or overlying Victor Bay shale around homogeneous, noncompactable, impermeable mounds;

4. residence in the domal trap of a gas cap which impeded further vertical migration of metalliferous fluids and created reducing conditions necessary for sulphide precipitation (Arne et al., 1991).

This set of conditions does not appear to prevail in most other parts of the Milne Inlet Graben, where showings have a different but partially overlapping set of controlling factors. Faults clearly play roles in almost all of the showings, but the presence of anticlines is not always demonstrable, and mounds are scarce east of the Red Rock valley area.

It is not surprising that an actively rifting marine basin should contain highly active fluid and/or gas systems concentrated at structural weaknesses. The recognition of possible seep mounds has implications for the history of carbonate sedimentary systems as well as for the understanding of cold-seep structures, of the stratigraphic architecture of the Borden Basin, and of the fluid-flow history and base-metal prospectivity of the Milne Inlet Graben.

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